STATISTICAL RESEARCH ON
ANALYSIS AND PREVENTION OF
ENVIRONMENTAL DEGRADATION

FINAL REPORT

— STATISTICS —

— OPERATIONS RESEARCH —

— MATHEMATICS —

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

DESMATICS, INC.

P.O. Box 618
State College, PA 16804

DESMATICS, INC.

P.O. Box 618
State College, PA 16804
Phone: (814)-238-9621
Fax: (814)-238-5731
e-mail: desmat1@aol.com

Applied Research in Statistics and Systems Analysis

STATISTICAL RESEARCH ON ANALYSIS AND PREVENTION OF ENVIRONMENTAL DEGRADATION

FINAL REPORT

Technical Report No. 157-5

March 1996

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

This research was supported by the Naval Research Laboratory under Contract No. N00014-94-C-2008.

19960327 102

Date: 10/16/95 Time: 7:46:27PM

Page: 1 Document Name: untitled

```
- 1 -  AD NUMBER: A299445
-- 2 -  FIELDS AND GROUPS: 13/1, 13/10
-- 5 -  CORPORATE AUTHOR: DESMATICS INC  STATE COLLEGE PA
-- 6 -  UNCLASSIFIED TITLE:     STATISTICAL ANALYSIS OF RESULTS FROM THE
--      1995 SURVEY OF CFC CONSUMPTION ON U.S. NAVY SHIPS.
-- 9 -  DESCRIPTIVE NOTE: TECHNICAL REPT.,
--10 -  PERSONAL AUTHORS: BURNS, KEVIN C.; SMITH, DENNIS E.
--11 -  REPORT DATE:     AUG   , 1995
--12 -  PAGINATION:     42P   MEDIA COST: $  6.00
--14 -  REPORT NUMBER:    TR-157-4
--15 -  CONTRACT NUMBER:  N00014-94-C-2008
--18 -  MONITOR ACRONYM:  XB
--19 -  MONITOR SERIES:   NRL
--20 -  REPORT CLASSIFICATION:  UNCLASSIFIED
--33 -  LIMITATION CODES:  1
```

EXECUTIVE SUMMARY

This Desmatics report, Statistical Research on Analysis and Prevention of Environmental Degradation, is the final deliverable submitted under Contract No. N00014-94-C-2008 to the Naval Research Laboratory. It provides a summary of the Desmatics technical effort, which involved development and application of statistical methods within a number of Navy environmental research areas.

During its research effort, Desmatics prepared four technical reports, two addressing the fundamental problem of analyzing environmental data with less-than-detectable concentrations, and two summarizing the results of NAVSEA surveys of CFC/Halon consumption in the fleet. These reports have been disseminated in accordance with the distribution list specified in the contract.

Desmatics also prepared fifty technical notes which document statistical findings and recommendations associated with a number of Navy environmental projects. Copies of these documents were provided to the cognizant Navy scientists and engineers. This report provides a list of the technical notes, which are available from Desmatics on request.

TABLE OF CONTENTS

1. INTRODUCTION

Under Contract No. N00014-94-C-2008 to the Naval Research Laboratory, Desmatics has conducted statistical research on problems associated with the Navy's environmental programs. This research has included the formulation of new methods for analyzing data with less-than-detectable contaminant concentrations, the development of a monitoring plan for the Navy's stockpile of ozone-depleting substances (ODSs), the design of test plans for experimental and sampling studies, and statistical data analysis and mathematical modeling. The overall Desmatics effort has involved statistical research on a number of technical problems within Navy environmental programs of the Naval Sea Systems Command (NAVSEA) and the Annapolis Detachment of the Naval Surface Warfare Center, Carderock Division (NSWCCD/A).

Desmatics' research on the analysis of data with less-than-detectable concentrations was documented in two technical reports provided to the Naval Research Laboratory. Two other reports provided analyses of NAVSEA surveys of shipboard usage of ozone-depleting substances. (Abstracts of these four reports are given in Section 9.) In addition, Desmatics prepared fifty technical notes which address statistical issues in a number of environmental research areas. These technical notes have been provided to the Navy scientists and engineers who were involved in those programs. This final report does not include copies of the technical notes, but a complete listing is provided in Section 10. Interested parties may obtain copies of any of the

technical notes from Desmatics upon request.

The research effort under this contract was focused primarily on four general areas within the Navy's environmental program:

(1) ozone-depleting substances,

(2) oily wastewater,

(3) graywater filtration membranes,

and (4) shipboard solid wastes.

In addition, Desmatics participated in a number of research efforts which do not fall into any of these general areas. The following chapter summarizes the overall Desmatics effort.

2. SUMMARY OF THE DESMATICS TECHNICAL EFFORT

Throughout this research effort, Desmatics worked closely with the Navy to ensure that appropriate statistical research support was given to a wide variety of environmental projects. Desmatics personnel attended numerous meetings in Washington, Annapolis and Philadelphia to discuss various aspects of these projects. A brief summary of the Desmatics effort is given below:

(1) Less-Than-Detectable Concentrations

Developed procedures for drawing improved inferences from environmental samples when all sample concentrations are reported as less than some detection limit.

(2) Ozone-Depleting Substances

Analyzed CFC/Halon survey results to determine required reserves until ships are modified or decommissioned.

Demonstrated that CFC consumption decreased from the 1994 to the 1995 survey periods, reflecting NAVSEA efforts to reduce that consumption.

Developed a monitoring plan to track future CFC/Halon consumption, to calculate confidence limits for reserve sufficiency and to flag unusual consumption patterns.

(3) Oily Wastewater

Developed test plans for oil filtration membranes and performed statistical analyses of data.

Analyzed data from laboratory tests in conjunction with the compensated ballast program, developed a test plan for an analytical study of oil-in-water measurement techniques.

Analyzed data from OCM studies, developed performance and reliability test plans for new monitors.

Developed performance test plan for HCOWS.

Characterized bilge oil and detergent concentrations from INSURV results.

(4) Graywater Filtration Membranes

Analyzed laboratory and pierside test data, compared feed concentrations and performance in different experiments.

Detected differences between laboratories performing chemical analyses.

(5) Shipboard Solid Wastes

Made recommendations for minimizing biases in evaluations of proposals for PWP production.

Analyzed solid waste generation rate data, demonstrating the differences between older and newer data.

(6) Other Research Areas

Analyzed performance data and made recommendations for future testing of EDG.

Developed initial test plan for vortex incinerator.

Discussed tradeoffs associated with the reliability test of the composite pump.

Performed sensitivity analyses of ship emissions model.

Analyzed blackwater/graywater disposal cost data and characterized the changes from 1991 to 1995.

The following sections of the report supply more details about the Desmatics research effort.

3. LESS-THAN-DETECTABLE CONCENTRATIONS

Many environmental sampling problems involve some specified regulatory or contractual limit (RL). Often the interest is in estimating p_{RL}, a specified percentile of the underlying contaminant concentration distribution corresponding to RL. Suppose any concentration greater than RL is classified as "positive" and any concentration less than or equal to RL is classified as "negative."

The focus of the Desmatics research effort was on obtaining a point estimate and lower confidence bound for the desired percentile p_{RL} based on a sample of observations, all of which are negative and nondetectable, known only to be less than some detection limit DL $\leq$ RL. In that situation, a lower confidence limit for p_{RL} can easily be calculated based on a binomial distribution, but that approach does not take into account the value of DL. Intuition would indicate that the smaller the reported detection limit, relative to RL, the lower the confidence limit should be for a given degree of confidence. Desmatics developed an approach which yields confidence limits that match intuition.

The usual assumption for contaminants present in small quantities is that they can be well modeled using the lognormal statistical distribution. That distribution was assumed for the procedure described in Desmatics Technical Report No. 157-1, <u>Estimating a Percentile of a Contaminant Distribution When All Observations Are Less Than a Detection Limit</u>, July 1994. The results of that research were also presented at the August 1994

annual meeting of the American Statistical Association.

While the lognormal assumption is fairly standard for contaminants present in small quantities, there are some cases in which the assumption of a normal distribution may be more reasonable. For example, if the cost of sampling is small relative to the cost of chemical analysis, composite samples may be used. Whatever the underlying distribution of contaminant concentrations, the distribution of concentrations in the composite samples will tend toward normality.

Contaminant concentrations can never follow a normal distribution exactly, since they must be nonnegative. However, the normal distribution should provide a reasonable approximation in many cases. Desmatics developed a method for finding a conservative lower confidence limit for the desired percentile assuming an underlying normal distribution. It is anticipated that this procedure will be conservative enough that the desired confidence level will be achieved even under small departures from the distributional assumption. This methodology was reported in Desmatics Technical report No. 157-3, <u>Drawing Inferences From Environmental Samples When All Observations Are Less Than a Detection Limit</u>, March 1995, and presented at the August 1995 meeting of the American Statistical Association. Abstracts of both of these technical reports are given in Section 9.

4. OZONE-DEPLETING SUBSTANCES

Chlorofluorocarbons (CFCs) are used in Navy air conditioning (AC) and refrigeration systems, as well as for some cleaning applications. Halons are used in fire suppression systems. These substances have been found to damage the ozone layer, and domestic production has ceased (31 December 1993 for Halons, 31 December 1995 for CFCs). Because these ODSs are used in mission-critical applications, the Navy has stockpiled reserves intended to last until ships are retired or converted to use alternative refrigerants. Desmatics has been extensively involved in first determining the size of the reserves needed and later in monitoring the drawdown of those reserves.

4.1 Determining the Size of the Reserve

Desmatics initially calculated statistical confidence bounds for fleet CFC-114 usage based on information from a survey conducted by the Naval Ship Systems Engineering Station (NAVSSES) in 1990. Those calculations were documented in [5][1]. Only 53 ships were included in that survey, which was restricted to a single type of refrigerant. The Navy subsequently decided that more comprehensive and current data was needed.

In May 1994, NAVSEA sent a survey to all ships in the fleet requesting data on consumption. Desmatics was one of the participants in developing that survey. Ships were asked to estimate

[1]Numbers in brackets refer to Desmatics, Inc. technical notes (e.g., [5] refers to Technical Note No. 157-5). The same notation is used in succeeding chapters.

total consumption for Halon 1211 and Halon 1301 fire-suppression systems, chilled-water AC plants using CFC-11, CFC-12 or CFC-114, and CFC-12 cargo and ships-stores refrigeration plants. Respondents were asked, if possible, to separate normal usage from consumption caused by catastrophic failures or accidental discharges. Halon data was requested for a four-month period from 1 January 1994 to 30 April 1994, while CFC data was requested for the entire preceding year (1 May 1993 to 30 April 1994). The shorter period for Halons was chosen to match available data from the Navy supply system. Responses were received from 209 ships, and a statistical analysis of the data was provided in Desmatics Technical Report No. 157-2, Statistical Analysis of Results From a Survey of Halon and CFC Consumption on U.S. Navy Ships, August 1994. NAVSEA used these results as the initial basis for sizing the required reserves.

In May 1995, NAVSEA sent a second survey to the fleet requesting CFC consumption data. There were two primary purposes for this survey: to obtain additional information on reserve requirements and to measure the effects of policies designed to reduce consumption. An analysis of the data from that survey was provided in Desmatics Technical Report No. 157-4, Statistical Analysis of Results From the 1995 Survey of CFC Consumption on U.S. Navy Ships, August 1995. One important conclusion from that analysis was that CFC consumption had decreased significantly from that reported in the previous survey period.

4.2 Monitoring the Reserve

NAVSEA has pursued an aggressive policy to reduce shipboard ODS consumption through increased training and the installation of leak detection and refrigerant recovery equipment. Desmatics has been involved in developing statistical procedures to help assess the effects of these policies. Statistical process control (SPC) techniques can aid in this assessment. Application of those techniques to shipboard ODS consumption was discussed in [12].

In order for ODS leakage rates to ever be in statistical control, sources of excess variability must be identified. In [15], Desmatics discussed an approach for attempting to identify at least some of the sources of variability, and for possibly setting up an SPC plan. That plan requires that consumption data be available for multiple time periods, but the only reliable data at that time was for a single survey period. In an attempt to identify proxy measures of consumption, which are available for additional time periods, Desmatics examined maintenance and supply data. No accurate substitute measures were found, as documented in [28], so the institution of an SPC program had to await the gathering of additional consumption data.

In February 1995, the ODS stockpile became fully operational. NAVSEA has been given the task of monitoring the drawdown of the Navy's reserve of ODSs to ensure that the reserve will not be prematurely depleted prior to the date when the Navy no longer has any ODS requirements. That date is approximately 50 years in the future.

In [31], Desmatics provided an overview of some procedures suggested for use in an early warning system. Using this as a starting point, Desmatics developed a concept for an overall monitoring system, and began its implementation. However, because not all required data is currently available, only preliminary results have been obtained. The following two subsections discuss the framework of the monitoring system and its initial implementation.

4.2.1 The Monitoring System

The monitoring system involves two subsystems:

(1) preliminary screening

and (2) tracking and early warning.

Each of these subsystems is automated to some degree. The first provides an examination of monthly ODS requisitions data to detect possible instances of abnormal usage by individual end users or issues to unauthorized users. The second is based on statistical techniques for identifying changes in usage which could result in unacceptable levels in the reserves.

The preliminary screening subsystem checks the reported ODS inventory issue data and confirms that material from the Navy's ODS Reserve is provided to authorized users only. This is accomplished by comparing approved requisitions with the current list of authorized users. The preliminary screening subsystem also checks for possible out-of-the-ordinary data such as material issues that significantly exceed typical requisition quantities. Any reported data that appears incorrect or abnormal is

brought to the attention of NAVSEA and is tagged for further investigation.

The tracking and early warning subsystem generates tables and graphs comparing (1) actual with projected ODS usage and (2) actual with projected drawdown of the ODS reserve. This subsystem also estimates the degree of confidence that the existing ODS stockpile will be sufficient to support the Navy for the intended length of time, and calculates the size of the expected surplus or shortfall.

The analysis in this subsystem is based on a number of assumptions, including that of an underlying stable statistical process for each ODS. Therefore, the assumptions must be continually checked as new usage data becomes available. The subsystem uses quality control charts and statistical tests to evaluate the reasonableness of the assumptions and to determine whether the analytical procedures need to be revised.

4.2.2 Preliminary Implementation of the Monitoring System

The Defense Supply Center (DSC)[2], which reports approved ODS issues and customer returns monthly, provides data on consumption to the monitoring system. Halon 1301 cylinder issue data, supplied by the Navy Inventory Control Point (NAVICP)[3], Mechanicsburg, PA, is also used in monitoring this ODS. The beginning date for collection of actual usage (issues and returns) data was 1 January 1995.

---

[2]Formerly the Defense General Supply Center (DGSC).

[3]Formerly the Ships Parts Control Center (SPCC).

The calendar year 1995 monthly DSC Navy ODS issues data (for CFC-11, CFC-12, CFC-114, Halon 1301, and Halon 1211) were reviewed for unusually large issues (relative to total installed charge) to identifiable individual surface ships or submarines, and to confirm that only authorized users had received the restricted substances. NAVICP's Technical Screening Expert System (TSES) data base was used in this screening. TSES provides the Authorized User List (AUL) by Unit Identification Code (UIC) for each ODS.

For the tracking and early warning subsystem, Desmatics developed a data base for the three CFCs (R-11, R-12, and R-114) and two Halons (1301 and 1211). This data base is used to estimate the projected mission-critical usage of these ODSs by fiscal year, to track actual monthly usage for comparison with projected usage, and to monitor the actual and projected drawdown of the Navy's ODS reserves. This data base was developed from inputs provided by three Naval Commands: NAVSEA, NAVAIR and MSC.

The projected NAVSEA usage of CFCs is based on scheduled new installations, conversions, or retirements of ship air conditioning and refrigeration plants and estimated normal usage and recovery rates. For each ship hull number, NAVSEA supplied CFC and Halon charges, together with a schedule of plant conversions and retirements. Desmatics estimated CFC and Halon normal usage and recovery rates from the analysis of responses to the NAVSEA ODS surveys, which were described in Section 4.1. Using these estimates together with the charge and schedule data, Desmatics projected NAVSEA ODS usage for each fiscal year until requirements

no longer existed. MSC and NAVAIR supplied estimated CFC and Halon usage and recovery data directly.

The initial sizes of each ODS reserve stockpile are based on procurement requirements which are documented in CNO ltr 5090 Ser N451I/5U597641, 01 June 1995 for the CFCs and Halon 1301. An additional estimated NAVSEA reserve of Halon 1301 cylinders and the estimated reserve of Halon 1211 are based on NAVSEA ltr 9510 Ser 03V2/156, 21 July 1994. These estimates are tabulated below:

ODS	Reserve (lbs)
CFC-11	121,000
CFC-12	1,343,000
CFC-114	1,750,000
Halon 1301	2,356,000
Halon 1211	53,845

Whenever the procurement requirement for any ODS is revised, or modifications to the conversion/retirement schedules or projected usage data are released by the Navy, the data base developed by Desmatics will need to be updated to reflect any changes.

The tracking and early warning subsystem is designed to produce outputs summarizing the stockpile status up to the date of the most recent ODS monthly issues and returns supplied by DSC. Table 1 and Figures 1 and 2 provide examples of the output tables and graphs produced by this subsystem for CFC-12. Table 1 and Figure 1 show cumulative usage from 1 January through 31 December 1995. Figure 2 illustrates the drawdown of the reserve over that period. Similar tables and graphs are available for the other ODSs. However, because of a lack of estimated normal usage and recovery data for Halon 1211, the outputs for this ODS

currently are limited to a portrayal of the actual monthly drawdown of the reserve.

Data upon which the monitoring system is based can be used to evaluate potential changes in Navy policy regarding ODSs. For example, given that domestic CFC production has ceased, ships are finding it increasingly difficult to obtain CFC-12 for galley equipment, which is not mission critical. One potential solution to this problem would be for NAVSEA to retain recovered CFC-12 rather than return it to the stockpile.

Initial reserve requirements of CFC-12 were based on estimated usage rates and projected force structures. No allowance was made for the variability inherent in those estimates. However, because of decreasing usage rates, it is now possible to conclude, with a high degree of statistical confidence, that the stockpile will not be depleted prematurely, even if recovered CFC-12 is not returned. The analysis leading to this conclusion is documented in [50]. Table 2 provides a complete list of the technical notes produced in this research area.

CFC-12 DSC RESERVE STOCKPILE

Fiscal Year	Month	Projected Usage with Recovery	Projected Usage without Recovery	Reported DSC Issues	Reported DSC Returns	Reported Net Usage	Cumulative Projected Net Usage	Cumulative Reported Net Usage	Projected Remaining Stockpile with Recovery	Reported Remaining Stockpile with Returns	Projected Remaining Stockpile without Recovery	Reported Remaining Stockpile without Returns
		lbs	lbs	lbs	lbs	lbs	lbs	lbs	lbs	lbs	lbs	lbs
									1,343,000	1,343,000	1,343,000	1,343,000
1995	Jan-95	14,833	15,987	2,880	488	2,392	14,833	2,392	1,328,167	1,340,608	1,327,013	1,340,120
	Feb-95	14,833	15,987	3,330	3,713	(383)	29,666	2,009	1,313,334	1,340,991	1,311,026	1,336,790
	Mar-95	14,833	15,987	3,070	3,402	(332)	44,499	1,677	1,298,501	1,341,323	1,295,039	1,333,720
	Apr-95	14,833	15,987	30,780	210	30,570	59,332	32,247	1,283,668	1,310,753	1,279,053	1,302,940
	May-95	14,833	15,987	2,610	2,284	326	74,165	32,573	1,268,835	1,310,427	1,263,066	1,300,330
	Jun-95	14,833	15,987	5,040	1,740	3,300	88,998	35,873	1,254,002	1,307,127	1,247,079	1,295,290
	Jul-95	14,833	15,987	38,305	1,785	36,520	103,830	72,393	1,239,170	1,270,607	1,231,092	1,256,985
	Aug-95	14,833	15,987	9,685	1,752	7,933	118,663	80,326	1,224,337	1,262,674	1,215,105	1,247,300
	Sep-95	14,833	15,987	1,405	4,013	(2,608)	133,496	77,718	1,209,504	1,265,282	1,199,118	1,245,895
1996	Oct-95	11,749	13,019	15,435	6,143	9,292	145,245	87,010	1,197,755	1,255,990	1,186,099	1,230,460
	Nov-95	11,749	13,019	3,015	4,268	(1,253)	156,994	85,757	1,186,006	1,257,243	1,173,080	1,227,445
	Dec-95	11,749	13,019	6,510	4,995	1,515	168,743	87,272	1,174,257	1,255,728	1,160,061	1,220,935

Beginning Stockpile: 1,343,000 lbs

Table 1: CFC-12 Projected and Reported Usage (Pounds) Beginning January 1995

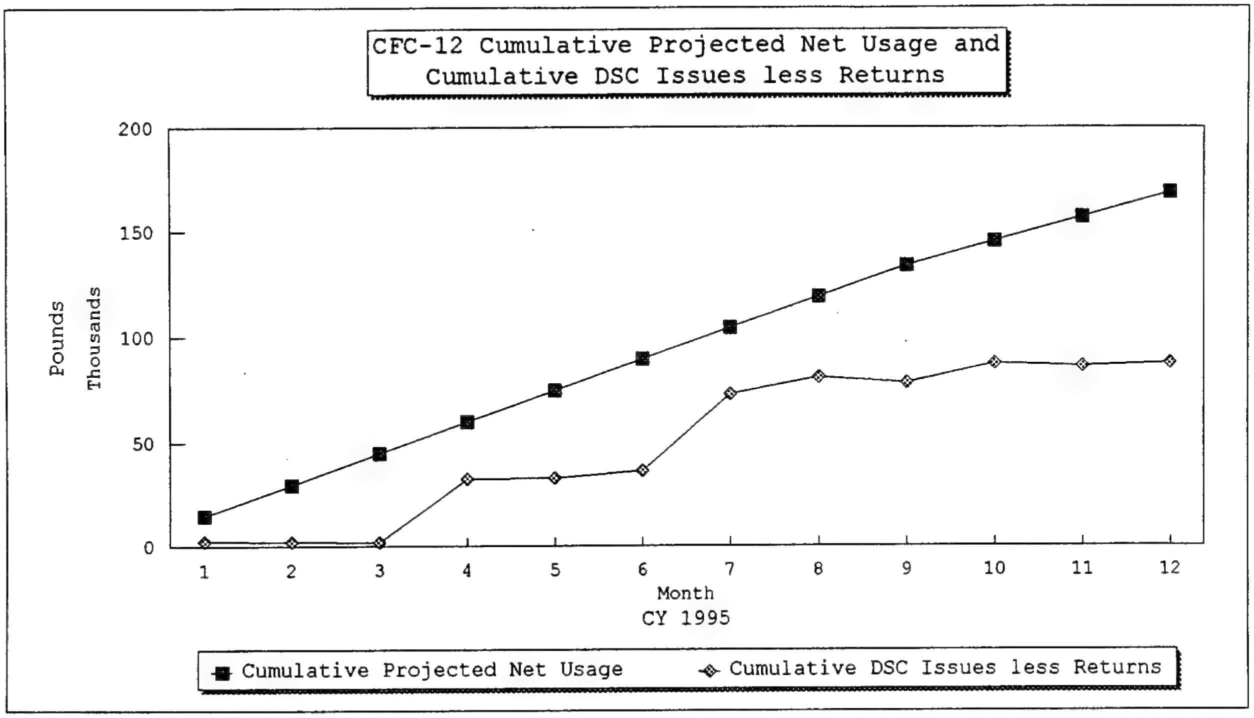

Figure 1: CFC-12 Cumulative Projected and Reported Usage

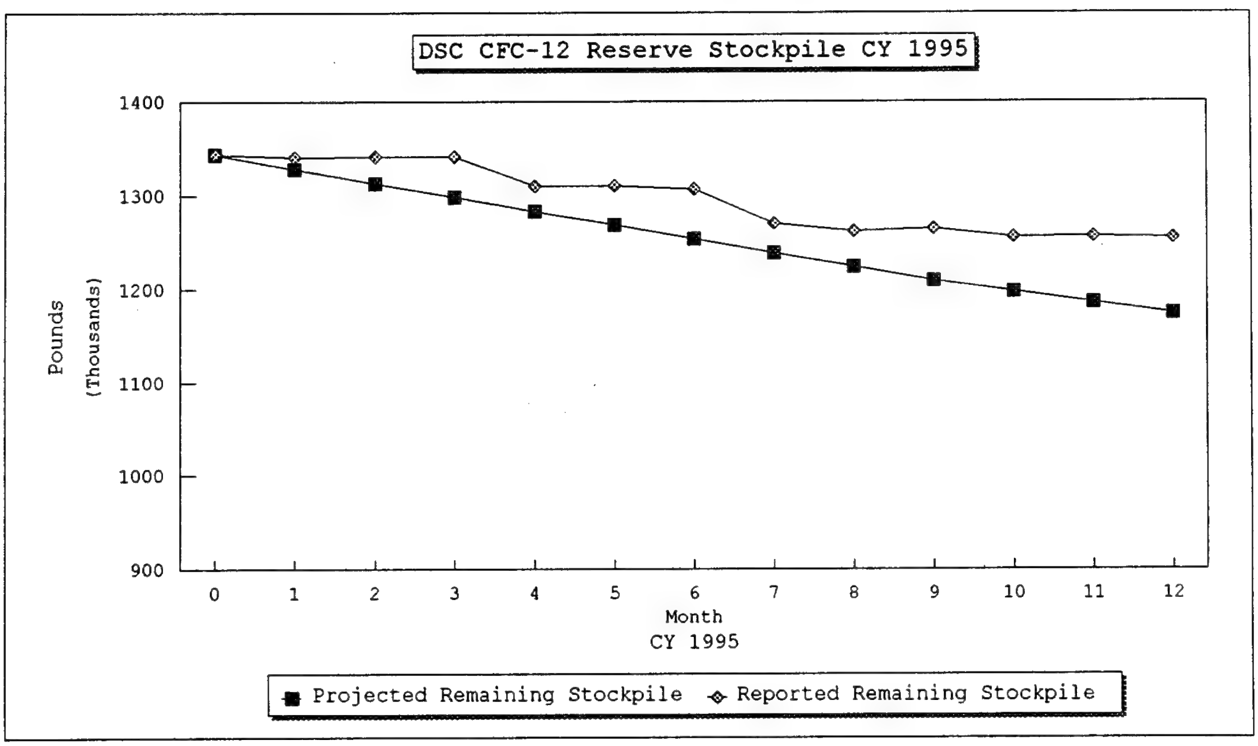

Figure 2: Drawdown of the DSC CFC-12 Reserve

Technical Note No.	Title
157-5	Statistical Confidence Bounds on Mission Critical Inventory Requirements for CFC-114
157-12	Some Thoughts on Statistical Process Control Applied to the Leakage of Ozone-Depleting Substances
157-15	A Preliminary Approach for Attempting to Identify Sources of Variability in Shipboard Leakage Rates of Ozone-Depleting Substances
157-28	Examination of the Relationships Between Maintenance, Supply and Consumption Data for R-12 and R-114
157-31	Procedures for Use in an Early Warning System for Monitoring Depletion of the Navy's ODS Stockpile
157-50	A Preliminary Analysis of the Adequacy of the Navy's CFC-12 Stockpile

Table 2: Desmatics, Inc. Technical Notes in the Area of Ozone-Depleting Substances.

5. OILY WASTEWATER

Shipboard bilge water may contain significant quantities of oil, as well as other contaminants. On ships using compensated ballast fuel systems, the compensating water may also contain oil. The Navy is investing considerable resources into developing treatment and monitoring systems for this wastewater, and Desmatics has had extensive involvement in this research effort. A list of the technical notes documenting the Desmatics research efforts in this area is provided in Table 3 at the end of this chapter.

5.1 Oil Filtration Membranes

Shipboard oily wastewater is processed using an oil/water separator (OWS). The separators are designed to reduce oil concentrations to less than 20 mg/l in port and 100 mg/l at sea. It is anticipated that future regulations will require the Navy to reduce oil concentrations to as low as 5 mg/l. In order to satisfy this requirement, the Navy is currently developing oil-filtration membranes for treating OWS effluent. It is anticipated that the membranes will remove other contaminants along with the oil. These systems have been tested in the laboratory, aboard ship, and at a shoreside facility.

Desmatics has been heavily involved in this research effort, first in the development of test plans to ensure that appropriate and sufficient experimental data is obtained for evaluating candidate membrane systems. Desmatics has also provided statistical

analyses of test data to ensure the validity of the conclusions drawn from these tests.

The bilge waste treatment system installed at Naval Weapons Station Earle consisted of a Navy OPB-10NP Oil/Water Separator (OWS) in series with two parallel banks of polysulfone ultra-filtration membrane cartridges. Bilge water from Navy ships was brought to the treatment facility in tank cars and processed in batches of up to 10,000 gallons. There were insufficient re-sources to analyze multiple grab samples over time, so composite sampling was used instead. Desmatics analyzed composite sample data obtained between August 1991 and September 1993. The oil analysis results were documented in [4], and the results for fourteen metals were presented in [8].

The Navy planned to test a new type of ceramic membrane at Earle, and Desmatics provided recommendations for those tests [3]. Those recommendations covered the type of sampling (grab vs. composite), the number of test runs and quality control considerations. In [7], recommendations were provided for a laboratory demonstration of a ceramic membrane prototype system.

A number of different types of membranes have been tested at NSWCCD/A. In [16], Desmatics provided an analysis of data from nine small-scale membranes. These tests were generally continued until the membranes fouled and permeate flux dropped to unaccep-table levels. The analysis focused on summarizing permeate qual-ity over the course of a test run. Desmatics also examined the effects of various test factors, such as detergent concentra-tions, trans-membrane pressure, cross-flow velocity and cleaning.

A subsequent memo to NSWCCD/A provided models for changes in flux rates over time.

Researchers at Annapolis next began plans for testing small-scale membrane units aboard ship. Recommendations for those tests were provided in [22]. That note also addressed the preparation of quality control samples to evaluate laboratory reliability and a recommended experiment to evaluate methods for measuring detergent concentrations. Further recommendations for shipboard testing were provided in [26], including a discussion of the trade-offs between sample analysis costs and information gained from testing. Similar recommendations for the second phase of shipboard testing were provided in [29].

Throughout this research effort, Desmatics has performed statistical analyses of test data. An analysis of data from two small-scale laboratory prototype units was given in [30]. A full-scale laboratory system was evaluated in [34]. Most recently, Desmatics prepared three technical notes discussing the results of shipboard tests: oil [39], metals [42], and measures of organic contamination (BOD, COD and TSS) [47].

5.2 Compensated Ballast Refueling

Compensated ballast ships maintain varying amounts of fuel and water in their fuel tanks. After refueling, the tanks are essentially full of fuel oil. As the fuel is used, firemain water is pumped into the tanks to maintain the ship's seakeeping characteristics. During refueling, this compensating water is discharged overboard. There is concern that the discharged water

could contain significant amounts of oil.

The Navy is planning to monitor oil concentrations in shipboard compensating ballast water. Samples will be withdrawn from pitot tubes inserted in the ship's piping systems. It is generally recognized that such samples must be withdrawn isokinetically to be truly representative. However, it is difficult to maintain isokinetic conditions when sampling during refueling operations. Therefore, an experiment was conducted at the Philadelphia Detachment, Carderock Division, Naval Surface Warfare Center (NSWCCD/P) in an attempt to quantify the effects of departures from isokinetic flow. Desmatics analyzed the data from this test and found that modest departures from isokinetic conditions had little effect on measured oil concentrations [6].

For shipboard sampling, there will necessarily be some length of piping between the pitot tube and the sampling port. There is some concern that oil may be retained in the subsidiary piping system, resulting in lower concentrations at the sampling port. An experiment to address this concern was conducted at NSWCCD/P, and Desmatics analyzed the resulting data [9]. Samples taken from the longer sampling line were not found to be significantly different from those taken from the shorter line.

A second study was conducted in an effort to quantify the effect of the transport line on the oil concentrations. This experiment used a longer transport line than in the first study. Concentrations in samples from the longer transport line were found to be significantly higher then those in the short line [19], contrary to expectations. It was concluded that some

extraneous factor not accounted for in the experiment was affecting those concentrations. Desmatics designed a third experiment to examine this problem [27], but that experiment has not yet been conducted.

In support of the compensated ballast program at Annapolis, Desmatics prepared two technical notes summarizing the results of the experiments conducted at Philadelphia [21], [25]. These notes bring together the results of the various tests and provide recommendations for further research.

As another part of this research effort, Desmatics developed a test plan to quantify the accuracy and precision of laboratory methods for measuring oil concentrations in water samples. That plan considers different methods (Navy vs. EPA), types of water and fuel, and measurement instruments. The test plan has gone through several iterations, primarily because of logistics considerations and delays in the release of the new EPA test method. As such developments have arisen, memos have been sent to the appropriate personnel in Annapolis and Philadelphia detailing the revisions to the test plan and discussing the reasoning behind those revisions.

Most recently, the compensated ballast program has focused on developing laboratory and computer simulation models for studying oil concentrations during refueling. It is anticipated that both small-scale and full-scale models will be constructed. These models will be used both to quantify the extent of the oil discharge problem and to investigate the effects of various changes to the fuel tanks. Desmatics personnel have attended a

number of meetings at NSWCCD/P to provide statistical input for these modeling efforts.

5.3 Oil Content Monitors

The Navy uses oil content monitors (OCMs) to regulate the discharge of oily waste. These monitors are designed to alarm when oil concentrations exceed a specified setpoint and thereby cause the wastewater to be recirculated to the OWS. When oil concentrations are below the critical level, the OCM should allow overboard discharge.

Several OCMs have been evaluated by the Navy over the years. In [1], Desmatics compiled the results of five studies of the Shimadzu/Parmatic OCM and three studies of the Baird Model B-1 OCM. These two types of monitor had been selected for possible use in conjunction with shipboard compensated ballast refueling studies. New analyses were performed to compare results from different studies. There were significant differences between the two types of monitor as well as differences in performance for the same type of monitor in different studies.

Most laboratory OCM tests have evaluated performance using just oil injected in water. The monitors also need to perform correctly (make acceptable decisions) in the presence of other contaminants. The Navy has identified four contaminants which are likely to interfere with OCM performance: particulates, air bubbles, detergents and color. Desmatics developed a test plan for a laboratory OCM evaluation with those interferences present, both singly and in combination [32]. The Navy also needs OCMs to

be reliable. A discussion of appropriate reliability tests was provided in [33].

5.4 High-Capacity Oil/Water Separator

The Navy has developed a high-capacity oil/water separator (HCOWS) for processing bilge water aboard aircraft carriers. The HCOWS is designed to meet in-port discharge standards while processing bilge water at 100 gpm. For the less stringent at-sea standards, the equipment is designed to operate at 200 gpm. Desmatics developed a test plan for determining whether these goals were being met [2].

The recommended test plan was designed to be conducted in two phases. In the initial phase, samples would be collected at three flow rates: 100, 150 and 200 gpm. The results of this testing would be used to estimate optimal flow rates for HCOWS operation. A second phase of testing would then be conducted with the intention of demonstrating acceptable performance at those flow rates. An alternative plan was also provided in case two-phase testing was not possible.

5.5 Bilge Waste Characterization

The performance of either an OWS or an OCM can be adversely affected by the presence of detergents in bilge water. Therefore, it is important to characterize detergent concentrations throughout the fleet. An earlier Navy laboratory study showed that these concentrations can be approximated by twice the difference between "apparent" and "actual" oil concentrations, as

measured by infrared spectrophotometry before and after filtering the extraction through silica gel. Since the silica gel may filter out contaminants other than detergents, this approximation may not work as well with shipboard bilge water as it did in the laboratory. Nevertheless, it should give some indication of detergent concentrations.

Desmatics analyzed a set of OWS effluent data obtained from recent Inspection and Survey (INSURV) results. Additional data was taken from pierside and shipboard evaluations of the Model 3F OWS and shipboard evaluations of two OCMs. That analysis was documented in [10]. A subsequent note [10A] supplemented those results with an analysis of oil concentrations found during those tests.

Technical Note No.	Title
157-1	Summary of OCM Test Results
157-2	Recommendations for the HCOWS Performance Evaluation Aboard the USS Eisenhower
157-3	Recommendations for Testing Ceramic Membrane Prototype System at Naval Weapons Station Earle
157-4	Analysis of Composite Sample Data From Bilge Waste Treatment System at Naval Weapons Station Earle
157-6	Statistical Analysis of Data From the Isokinetic Test of the Pitot Tube Sampler
157-7	Recommendations for Testing the Ceramic Membrane Oil Filtration Prototype System
157-8	Statistical Analysis of Metals Data From Earle Oily Waste Treatment Facility
157-9	Statistical Analysis of Data From the Oil Transport Study
157-10	Estimated Detergent Concentrations in Bilge Water
157-10A	Estimated Detergent and Oil Concentrations in Bilge Water
157-16	Preliminary Analysis of Membrane Filtration Test Results
157-19	Statistical Analysis of the Second Oil Transport Study
157-21	Summary of Results: Oil in Water Sampling Studies
157-22	Recommended Test Plan for Oil Filtration Membranes
157-25	Oil in Water Sampling Studies: Summary and Conclusions
157-26	Recommended Test Plan for Shipboard Test of Oil-Filtration Membranes

Table 3: Desmatics, Inc. Technical Notes in the Area of Oily Wastewater Treatment.

Technical Note No.	Title
157-27	Preliminary Recommendations for Transport Study
157-29	Recommendations for Second-Phase Shipboard Tests of Oil-Filtration Membranes
157-30	Statistical Analysis of Data from Laboratory Tests of Oil-Filtration Membranes
157-32	Recommended Test Plan for Evaluating OCM Performance
157-33	Discussion of OCM Reliability Test
157-34	Preliminary Analysis of Data From Tests of Full-Scale Oily Waste Membranes
157-39	Statistical Analysis of Data From Shipboard Tests of Oil Filtration Membranes: Oil Concentrations
157-42	Statistical Analysis of Data From Shipboard Tests of Oil Filtration Membranes: Metal Concentrations
157-47	Statistical Analysis of Data From Shipboard Tests of Oil Filtration Membranes: COD, BOD and TSS

Table 3 (cont.): Desmatics, Inc. Technical Notes in the Area of Oily Wastewater Treatment.

6. GRAYWATER FILTRATION MEMBRANES

Researchers at NSWCCD/A are investigating the use of membrane filtration systems to treat shipboard graywater and blackwater. Most testing to date has been restricted to graywater. Desmatics has been involved in planning these tests and providing statistical analyses of the test results.

In 1994, a small-scale model of a two-stage filtration system was tested at the Annapolis laboratory. The system used ultrafiltration membranes in the first stage and nanofiltration membranes in the second stage. The first-stage permeate was fed to the second-stage filter for further treatment, either continuously (feed and bleed) or in batch mode. Three measures of effluent quality were obtained: biochemical oxygen demand (BOD), total suspended solids (TSS) and fecal coliform most probable count (FC). FC counts were generally less than detectable, so Desmatics restricted its analysis to BOD and TSS [17]. Lognormal distributions were fit to the contaminant concentrations at each sampling concentration, and the 90^{th} percentiles were estimated. A subsequent memo provided upper bounds for those percentiles.

During 1995, more extensive testing of this type of system was conducted, both in the laboratory and at the pier. Two laboratory systems were tested. The first was a 3 gpm system with 64 large-bore ultrafiltration membranes in the first stage and a single nanofiltration membrane in the second stage. The second laboratory prototype consisted of a single 0.5 gpm ultrafiltration membrane bundle. A statistical analysis of the data

from those tests was provided in [48].

Following the laboratory demonstration, a full-scale two-stage membrane system was tested pierside alongside the L.Y. Spear (AS-36). Samples were sent to two outside laboratories for chemical analyses. Desmatics first checked for and found statistically significant differences between the results from the two laboratories [35]. As a result, subsequent analyses were restricted to data from a single laboratory.

Because of the volume and complexity of the data obtained from the pierside tests, analyses of different contaminants were presented individually in a series of eight technical notes. [36, 37, 38, 40, 41, 43, 44, 45]. In addition, the first three notes in this series were updated following the receipt of additional data from the laboratories performing the chemical analyses. These notes address membrane performance in removing the different contaminants and compare the pierside results to those obtained in the laboratory. A complete listing is provided in Table 4.

Technical Note No.	Title
157-17	Preliminary Analysis of Two-Stage Graywater Filtration Membrane Laboratory Test Results
157-35	Differences Between Laboratories in Graywater Contaminant Measurements
157-36	Statistical Analysis of BOD Results From Pierside Graywater Filtration Tests
157-36A	Updated Analysis of BOD Results From Pierside Graywater Filtration Tests
157-37	Statistical Analysis of TSS Results From Pierside Graywater Filtration Tests
157-37A	Updated Analysis of TSS Results From Pierside Graywater Filtration Tests
157-38	Statistical Analysis of FC Results From Pierside Graywater Filtration Tests
157-38A	Updated Analysis of FC Results From Pierside Graywater Filtration Tests
157-40	Statistical Analysis of COD Results From Pierside Graywater Filtration Tests
157-41	Statistical Analysis of Oil/Grease Results From Pierside Graywater Filtration Tests
157-43	Statistical Analysis of TOC Results From Pierside Graywater Filtration Tests
157-44	Statistical Analysis of TDS Results From Pierside Graywater Filtration Tests
157-45	Statistical Analysis of TKN Results From Pierside Graywater Filtration Tests
157-48	Statistical Analysis of Results From Laboratory Graywater Filtration Tests

Table 4: Desmatics, Inc. Technical Notes in the Area of Gray-Water Filtration Membranes.

7. SHIPBOARD SOLID WASTES

The Navy is planning for the installation of a new generation of solid waste processing equipment throughout the fleet. There are four types of equipment being developed: a large pulper, a small pulper, a plastics waste processor (PWP) and a metal/glass shredder. Desmatics has been involved in various aspects of the solid waste program.

As part of the solid waste program, the Navy constituted a technical panel to review a number of proposals for PWP production. It was desirable to conduct this review in such a way as to avoid any bias which might arise as a result of the order in which the proposals are evaluated. Because a number of proposals were to be reviewed by each evaluator, care had to be taken to eliminate, or minimize, any effects of the order in which the proposals were reviewed. For example, it is clear that it would be unwise for each evaluator to review the proposals in the same order.

A primary concern in a situation such as this is the possibility of "carry-over" effects. These effects arise when a reviewer's evaluation of a proposal influences his evaluation of the following proposal. There are two main steps that can be taken to guard against these effects. The first is to insure that there is a reasonable period of time (e.g., a day or at least a few hours) between succeeding proposal evaluations. The second is to use a statistically based design that protects against possible sequence effects. Desmatics provided a recom-

mended plan [18] that incorporated both of these steps.

In order for each ship to receive an equipment suite capable of processing the shipboard-generated solid waste, both the processing rate of each equipment type and the generation rate for each stream of solid waste must be known. To aid in the determination, Desmatics conducted statistical analyses aimed at estimating the generation rate, in pounds/person/day, for each solid waste stream. Because PWPs will be the initial solid waste equipment installed in the fleet, Desmatics analyzed plastic waste generation data from shipboard surveys conducted by NSWCCD/A personnel [23]. Although data was also available in the 1971 Naval Shipboard Refuse Study[4] (NSRS), it was obvious that generation rates had changed over time, making the older data irrelevant.

Therefore, the plastic waste analysis was restricted to recent data (1987 - 1994) from three ships. The estimated generation rate was .196 pounds/person/day. The 95% confidence interval for the mean was (.127, .264). This interval is fairly wide, reflecting the fact that only a small amount of data was available for analysis.

For the other solid waste categories (glass/metal, food, and paper/cardboard) differences between the data from the 1971 study and the recent data were not obvious. For these three categories, Desmatics compared the recent data to the older data. As documented in [46], there are significant differences between the

---

[4]Naval Ship Engineering Center, Naval Shipboard Refuse Study, Hyattsville, MD, 1971.

two data sets. Food waste generation rates have increased over the last twenty years. The estimated rates for the other two categories are also higher for the newer data, but the changes from 1971 are not statistically significant, perhaps because the new data base is so limited. A data base of only three ships cannot be expected to provide very precise generation rate estimates. There is clearly a need to develop a more extensive modern data base.

There are two main approaches for obtaining such data. The first is for NSWCCD/A personnel to participate in shipboard surveys, as they have in recent studies, either by analyzing off-loaded solid waste or by actually monitoring refuse collection aboard ship. The second is for another survey patterned on the NSRS survey to be implemented.

The second approach has the advantage of being able to provide an extensive fleet-wide data base, with the attendant disadvantage of little centralized control over solid waste collection, classification and weighing. On the other hand, the control provided by the first approach is offset by higher costs and data from only a few ships.

An NSRS-type survey would not provide the control that might be desired. However, with the increased emphasis on environmental concerns within the Navy, a high degree of cooperation in the fleet and reasonably accurate results might be expected.

Perhaps the most cost-effective approach to gathering additional solid waste generation rate data would be to combine the two approaches. Conceptually, the data collection that is sub-

ject to more direct control by NSWCCD/A could be used to make statistical adjustments to the more inclusive data base that could be obtained by an NSRS-type survey.

Table 5 contains a list of the technical notes prepared in the shipboard solid waste area of the Navy's environmental programs. In addition to these technical notes, which document the studies described in the previous paragraphs, Desmatics also contributed to the initial design of laboratory tests to evaluate the feasibility of solid waste processing and storage methods for application on the NAVSEA New Attack Submarine (NSSN).

Technical Note No.	Title
157-18	Recommended Plans for Randomizing Proposal Evaluations To Be Made by a Technical Review Panel
157-23	A Statistical Analysis of Plastic Waste Generation Rates Aboard Navy Surface Ships
157-46	A Statistical Comparison of Recent Shipboard Solid Waste Generation Rates With Those of 25 Years Ago

Table 5: Desmatics, Inc. Technical Notes in the Area of Shipboard Solid Wastes

8. OTHER RESEARCH AREAS

Desmatics has conducted research in a number of areas not included in the previous sections. These have been short-term investigations in support of the Navy's environmental programs. A list of the Desmatics technical notes documenting these research efforts is given in Table 6 at the end of this section.

8.1 Electrolytic Disinfectant Generator

The Navy is developing an Electrolytic Disinfectant Generator (EDG) for disinfecting shipboard potable water supplies. A series of tests were performed in Annapolis to investigate the effects of several factors on the performance of a prototype unit: potable water temperature, ambient conditions, water pressure and flow, and inclination angle. Each test run required twenty-four hours of continuous operation, so several months were required to complete the test series.

Desmatics performed a preliminary analysis of EDG performance when approximately half of the planned 63-run test series had been completed [13]. Only tentative conclusions could be drawn at that time because some of the experimental factors were highly confounded. Recommendations were made for selecting the next set of tests so as to reduce that confounding.

An updated analysis of EDG performance was documented in [20], following forty-one test runs. Significant effects were found for water temperature and pressure as well as ambient air temperature. The different test factors were still somewhat con-

founded, and further recommendations were made to reduce that confounding.

8.2 Vortex Incinerator

The Navy is developing a new vortex incinerator to treat shipboard blackwater, graywater and bilge water. In general, it is expected that the wastewater streams will first be processed through OWS (bilge water only) and membrane systems, with the concentrate being sent to the incinerator. Desmatics developed a test plan to obtain preliminary information about the variability of emissions (primarily NO_x and particulates) from the system [14].

While several factors could affect emissions, Desmatics recommended that these preliminary tests focus on only two: air flow rate and feed rate. A sixteen-run test was recommended, with these factors tested at only two levels each. Provision was made for multiple sampling within some test runs so that between-run and within-run variance components could be separated.

8.3 Composite Pump

When the Navy was planning a TECHEVAL of its new composite pump, neither the number of pumps to be tested nor the daily operating time had yet been determined. Each of these factors affects total test time and thus the risk of drawing erroneous conclusions. Desmatics examined those risks as a function of total test time [24]. Recommendations were made for adjusting the acceptance criterion because of the time constraints.

8.4 Ship Emissions

NAVSEA has developed a Ship Emissions Model (SEM) to estimate the amounts of various airborne exhaust emissions from Navy ships in selected geographical areas. Desmatics conducted a sensitivity analysis to determine which input factors were most critical in influencing model predictions [11]. The model was found to be highly sensitive to two factors: the number of at-sea days and the emission factors for two particular types of engine (GT LM2500 and GTG 501-K17).

This analysis was conducted at a time when the SEM was still under development, which limits the usefulness of the sensitivity analysis. Desmatics recommended that a thorough model validation be conducted and outlined methods for performing such a validation. Only after the model is completely validated can the Navy make confident decisions based on the output from that model.

8.5 Blackwater/Graywater Disposal Costs

In developing its new generation of waste disposal equipment, the Navy must consider not only environmental impacts but also cost trade-offs. Desmatics examined blackwater/ graywater disposal costs at Mediterranean ports for two survey periods, 1991 and 1995. The ship classes were put into five groups based on crew size by NSWCCD/A, and Desmatics examined differences between groups and over time [49].

This analysis was complicated by the fact that there were no blackwater/graywater disposal costs charged for a number of ship visits. There was some concern about the legitimacy of these

zero costs, so the analysis was performed both with and without these values included in the data set.

With the zeros deleted, there is a significant decrease in the overall average cost/day from 1991 to 1995, but no significant changes within the individual ship groupings. The change in the overall average is primarily a result of the fact that a much larger proportion of small ships visited these ports in 1995 than in 1991. If the zeros are legitimate, there have been significant decreases in the costs for the first three groups, which include all ships except amphibious assault ships and carriers.

Technical Note No.	Title
157-11	A Preliminary Sensitivity Analysis of the Westinghouse MTD Ship Emission Model
157-13	Preliminary Analysis of EDG Performance Tests
157-14	Suggested Preliminary Experiment for Vortex Incinerator Emission Testing
157-20	Updated Analysis of EDG Performance Tests
157-24	Comments on Reliability Testing of the Composite Pump
157-49	A Comparison of the Blackwater and Graywater Disposal Costs From 1991 and 1995

Table 6: Desmatics, Inc. Technical Notes in Other Research Areas.

9. TECHNICAL REPORTS PREPARED DURING THE RESEARCH EFFORT

Abstracts of the four formal technical reports prepared under this contract are given below. A more complete discussion of the research documented in these reports was given in Sections 3 and 4 of this report.

Technical Report No. 157-1 July 1994

ESTIMATING A PERCENTILE OF A CONTAMINANT CONCENTRATION DISTRIBUTION WHEN ALL OBSERVATIONS ARE LESS THAN A DETECTION LIMIT

Many environmental sampling problems involve some specified regulatory or contractual limit (RL). Often the interest is in estimating p_{RL}, the percentile of the underlying contaminant concentration distribution corresponding to RL. We will classify any concentration greater than RL as "positive" and any concentration less than or equal to RL as "negative." The focus of this paper is on obtaining a point estimate and a lower confidence limit for p_{RL} when all observations are negative and known to be less than some detection limit DL, where DL $\le$ RL.

Based on n negative observations (and no positive ones), a lower $100(1-\alpha)\%$ confidence limit for p_{RL} can be easily calculated based on a binomial distribution. However, this approach does not take into account the value of DL. Intuition would indicate that the smaller is the reported detection limit in a sample containing no detectable observations, the smaller the confidence limit should be for a given degree of confidence. This paper suggests an approach for calculating confidence limits that match intuition.

Technical Report No. 157-2 August 1994

STATISTICAL ANALYSIS OF RESULTS FROM A SURVEY OF HALON AND CFC CONSUMPTION ON U.S. NAVY SHIPS

The Naval Sea Systems Command (NAVSEA) needs to determine the total fleet requirements for ozone-depleting substances until they are phased out. To provide information about the necessary reserves of these substances during the outyears, NAVSEA recently conducted a survey of CFC/Halon usage in the fleet.

This document provides a statistical analysis of the data from the survey, which includes reported usage for CFC-11, CFC-

12, CFC-114, and Halon 1301. The information in this report can be used to estimate the required CFC/Halon reserves. The average consumption figures can be used as the basis for an expected value approach, while those corresponding to the statistical confidence levels can be used to provide various degrees of guarantee that the estimated reserve will not be depleted prematurely.

Technical Report No. 157-3 March 1995

DRAWING INFERENCES FROM ENVIRONMENTAL SAMPLES WHEN ALL OBSERVATIONS ARE LESS THAN A DETECTION LIMIT

Many environmental sampling problems involve some specified regulatory or contractual limit (RL). Often the interest is in estimating p_{RL}, the percentile of the underlying contaminant concentration distribution corresponding to RL. We will classify any concentration greater than RL as "positive" and any concentration less than or equal to RL as "negative." The focus of this paper is on obtaining a point estimate and a lower confidence limit for p_{RL} when <u>all</u> observations are negative and known to be less than some detection limit DL, where DL $\leq$ RL.

In an earlier report, a procedure was developed based on the assumption of an underlying lognormal distribution. That is the usual assumption for contaminants present in small quantities. However, there are many cases (e.g., when dealing with composite samples) in which the assumption of a normal distribution may be more reasonable. This report presents a method for finding a conservative lower confidence limit for the desired percentile assuming an underlying normal distribution.

Technical Report No. 157-4 August 1995

STATISTICAL ANALYSIS OF RESULTS FROM THE 1995 SURVEY OF CFC CONSUMPTION ON U.S. NAVY SHIPS

Production of chlorofluorocarbon (CFC) refrigerants will cease in the United States at the end of 1995. The Naval Sea Systems Command (NAVSEA) needs to monitor total fleet requirements of CFCs until they are phased out. Stockpile requirements for ozone-depleting substances were determined from the results of a survey covering the period from 1 May 1993 to 30 April 1994. A second survey was conducted for the period from 1 May 1994 to 30 April 1995 for two primary reasons: to provide additional information on reserve requirements and to measure the effects of policies designed to reduce fleet CFC consumption.

This report provides a statistical analysis of the data from the new survey, which includes reported usage for CFC-11, CFC-12 and CFC-114. The new results are compared to those from the ear-

lier survey, showing a significant reduction in CFC usage. Summary information in the report can be used to refine estimates of reserve requirements. Statistical confidence limits for CFC usage can be used to provide various levels of assurance that the reserves will not be depleted prematurely.

9. TECHNICAL NOTES PREPARED DURING THE RESEARCH EFFORT

For ease of reference, this section provides a complete list of the Desmatics technical notes prepared under this contract. As previously mentioned, Desmatics provided copies of the relevant technical notes to those Navy scientists and engineers who were involved in a particular research area. Interested parties may obtain copies of any of the technical note from Desmatics upon request.

[1] Technical Note No. 157-1 (9 February 1994), Summary of OCM Test Results

[2] Technical Note No. 157-2 (28 February 1994), Recommendations for the HCOWS Performance Evaluation Aboard the USS Eisenhower

[3] Technical Note No. 157-3 (8 March 1994), Recommendations for Testing Ceramic Membrane Prototype System at Naval Weapons Station Earle

[4] Technical Note No. 157-4 (17 March 1994), Analysis of Composite Sample Data From Bilge Waste Treatment System at Naval Weapons Station Earle

[5] Technical Note No. 157-5 (24 March 1994), Statistical Confidence Bounds on Mission Critical Inventory Requirements for CFC-114

[6] Technical Note No. 157-6 (19 April 1994), Statistical Analysis of Data From the Isokinetic Test of the Pitot Tube Sampler

[7] Technical Note No. 157-7 (19 April 1994), Recommendations for Testing the Ceramic Membrane Oil Filtration Prototype System

[8] Technical Note No. 157-8 (6 May 1994), Statistical Analysis of Metals Data From Earle Oily Waste Treatment Facility

[9] Technical Note No. 157-9 (6 June 1994), Statistical Analysis of Data From the Oil Transport Study

[10] Technical Note No. 157-10 (24 June 1994), Estimated Detergent Concentrations in Bilge Water

[10A] Technical Note No. 157-10A (28 June 1994), Estimated Detergent and Oil Concentrations in Bilge Water

[11] Technical Note No. 157-11 (5 July 1994), A Preliminary Sensitivity Analysis of the Westinghouse MTD Ship Emission Model

[12] Technical Note No. 157-12 (3 October 1994), Some Thoughts on Statistical Process Control Applied to the Leakage of Ozone-Depleting Substances

[13] Technical Note No. 157-13 (7 October 1994), Preliminary Analysis of EDG Performance Tests

[14] Technical Note No. 157-14 (12 October 1994), Suggested Preliminary Experiment for Vortex Incinerator Emission Testing

[15] Technical Note No. 157-15 (19 October 1994), A Preliminary Approach for Attempting to Identify Sources of Variability in Shipboard Leakage Rates of Ozone-Depleting Substances

[16] Technical Note No. 157-16 (19 October 1994), Preliminary Analysis of Membrane Filtration Test Results

[17] Technical Note No. 157-17 (8 November 1994), Preliminary Analysis of Two-Stage Graywater Filtration Membrane Laboratory Test Results

[18] Technical Note No. 157-18 (14 November 1994), Recommended Plans for Randomizing Proposal Evaluations To Be Made by a Technical Review Panel

[19] Technical Note No. 157-19 (16 November 1994), Statistical Analysis of the Second Oil Transport Study

[20] Technical Note No. 157-20 (21 November 1994), Updated Analysis of EDG Performance Tests

[21] Technical Note No. 157-21 (30 December 1994), Summary of Results: Oil in Water Sampling Studies

[22] Technical Note No. 157-22 (10 February 1995), Recommended Test Plan for Oil Filtration Membranes

[23] Technical Note No. 157-23 (14 February 1995), A Statistical Analysis of Plastic Waste Generation Rates Aboard Navy Surface Ships

[24] Technical Note No. 157-24 (17 February 1995), Comments on Reliability Testing of the Composite Pump

[25] Technical Note No. 157-25 (7 April 1995), Oil in Water Sampling Studies: Summary and Conclusions

[26] Technical Note No. 157-26 (18 April 1995), Recommended Test Plan for Shipboard Test of Oil-Filtration Membranes

[27] Technical Note No. 157-27 (1 May 1995), Preliminary Recommendations for Transport Study

[28] Technical Note No. 157-28 (8 May 1995), Examination of the Relationships Between Maintenance, Supply and Consumption Data for R-12 and R-114

[29] Technical Note No. 157-29 (12 June 1995), Recommendations for Second-Phase Shipboard Tests of Oil-Filtration Membranes

[30] Technical Note No. 157-30 (15 June 1995), Statistical Analysis of Data from Laboratory Tests of Oil-Filtration Membranes

[31] Technical Note No. 157-31 (16 June 1995), Procedures for Use in an Early Warning System for Monitoring Depletion of the Navy's ODS Stockpile

[32] Technical Note No. 157-32 (23 October 1995), Recommended Test Plan for Evaluating OCM Performance

[33] Technical Note No. 157-33 (23 October 1995), Discussion of OCM Reliability Test

[34] Technical Note No. 157-34 (24 October 1995), Preliminary Analysis of Data From Tests of Full-Scale Oily Waste Membranes

[35] Technical Note No. 157-35 (8 November 1995), Differences Between Laboratories in Graywater Contaminant Measurements

[36] Technical Note No. 157-36 (13 November 1995), Statistical Analysis of BOD Results From Pierside Graywater Filtration Tests

[36A] Technical Note No. 157-36A (18 December 1995), Updated Analysis of BOD Results From Pierside Graywater Filtration Tests

[37] Technical Note No. 157-37 (29 November 1995), Statistical Analysis of TSS Results From Pierside Graywater Filtration Tests

[37A] Technical Note No. 157-37A (18 December 1995), Updated Analysis of TSS Results From Pierside Graywater Filtration Tests

[38] Technical Note No. 157-38 (30 November 1995), Statistical Analysis of FC Results From Pierside Graywater Filtration Tests

[38A] Technical Note No. 157-38A (18 December 1995), Updated Analysis of FC Results From Pierside Graywater Filtration Tests

[39] Technical Note No. 157-39 (5 December 1995), Statistical Analysis of Data From Shipboard Tests of Oil Filtration Membranes: Oil Concentrations

[40] Technical Note No. 157-40 (18 December 1995), Statistical Analysis of COD Results From Pierside Graywater Filtration Tests

[41] Technical Note No. 157-41 (20 December 1995), Statistical Analysis of Oil/Grease Results From Pierside Graywater Filtration Tests

[42] Technical Note No. 157-42 (2 January 1996), Statistical Analysis of Data From Shipboard Tests of Oil Filtration Membranes: Metal Concentrations

[43] Technical Note No. 157-43 (2 January 1996), Statistical Analysis of TOC Results From Pierside Graywater Filtration Tests

[44] Technical Note No. 157-44 (2 January 1996), Statistical Analysis of TDS Results From Pierside Graywater Filtration Tests

[45] Technical Note No. 157-45 (3 January 1996), Statistical Analysis of TKN Results From Pierside Graywater Filtration Tests

[46] Technical Note No. 157-46 (4 January 1996), A Statistical Comparison of Recent Shipboard Solid Waste Generation Rates With Those of 25 Years Ago

[47] Technical Note No. 157-47 (17 January 1996), Statistical Analysis of Data From Shipboard Tests of Oil Filtration Membranes: COD, BOD, and TSS

[48] Technical Note No. 157-48 (18 January 1996), Statistical Analysis of Results From Laboratory Graywater Filtration Tests

[49] Technical Note No. 157-49 (31 January 1996), A Comparison of the Blackwater and Graywater Disposal Costs From 1991 and 1995

[50] Technical Note No. 157-50 (6 February 1996), A Preliminary Analysis of the Adequacy of the Navy's CFC-12 Stockpile